

# SPECIFICATION

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## **[Radiation Hardened Microcircuits]**

### **Federal Research Statement**

[The conditions under which this invention was made are such as to entitle the Government of the United States under paragraph I(a) of Executive Order 10096, as represented by the Secretary of the Air Force, to the entire right, title and interest therein, including foreign rights.]

### **Background of Invention**

[0001] The present invention is in the field of semiconductor device fabrication, and in particular, relates to the radiation hardening of microcircuits.

[0002] In standard microelectronics technology one of the finally processes undergone is an anneal of the finished circuit in forming gas (a mixture of hydrogen and nitrogen or argon) at temperatures in the range 380 ° C to 430 ° C for periods of up to 30 minutes. Rapid thermal annealing has also been used. The primary objective of these anneals is to passivate the interface (dielectric/semiconductor) of the metal-oxide-semiconductor field effect transistors (MOSFETs) in order to enhance the carrier mobility in the inversion channel of the transistor and to eliminate threshold voltage shifts due to the presence of interface states. The subsequent depassivation of the interface (involving removal or release of the bonded hydrogen atoms attached during the passivation anneal) by hot carrier injection from the inversion channel during normal operation is the process by which degradation and aging of the device occurs. Failure of the device is usually observed when the hot electron induced degradation results in device channel mobility or threshold voltage shift outside a range of values considered acceptable.

[0003] It is known that if the gas used during the passivation anneal is one in which the hydrogen component is replaced by deuterium, then the resistance of the transistor dielectric/semiconductor interface to hot electron degradation is substantially increased. This resistance to hot electron degradation is specifically related to replacement of silicon-hydrogen bonds at the interface by silicon-deuterium bonds.

[0004] U. S. Patent No. 6,143,632 addresses the problem of hot carrier degradation at the interface between the silicon substrate and the  $\text{SiO}_2$  gate oxide layer by introducing deuterium before the uppermost conductive layer is formed, i.e., the gate oxide is grown in a  $\text{D}_2\text{O}$  vapor atmosphere which then diffuses through the gate oxide to the  $\text{Si/SiO}_2$  interface. The final annealing step is performed in a deuterium atmosphere at about 400 to 550 ° C for 30 minutes.

[0005] Other research has addressed the issue of electrical stress induced leakage currents (SILC) through the gate dielectric itself of the MOSFET. In this case, electrical charge is injected into the gate dielectric by application of a large electric field between the gate electrode and the substrate/source/drain contacts of the device. The mechanism invoked is the so-called Fowler-Nordheim tunneling. This becomes significant only when the electric field exceeds values of about  $4 \text{ MV cm}^{-1}$ . Device operating voltages are usually such that this regime of operation is avoided. In this case, it has been demonstrated that annealing of the finished devices in deuterium containing gas can result in an improved resistance to SILC. If the dielectric itself ( $\text{SiO}_2$ ) is grown in a wet atmosphere ( $\text{D}_2\text{O} + \text{O}_2$ ) then additional improvements in resistance to SILC can be obtained.

[0006] There is an important difference between radiation hardening a circuit and hardening a particular device within a circuit to improve resistance to hot carrier degradation or SILC. A circuit is comprised of three important areas where there are dielectrics that can be a source of radiation sensitivity. These areas are: (a) the gate oxide of the device (elemental transistor); (b) the field or isolation oxide (isolating one device from its neighbor); and (c) the isolation layer between interconnect lines (usually metallic) which link device to device or device to the

outside world. For most purposes it is the field or isolation oxide (b) which is the most important in radiation hardness. The gate oxide (a) is most important in device reliability and lifetime. The isolation layer between interconnect lines (c) may be important for overall circuit failure, but its importance for radiation hardness is unknown.

[0007] Current annealing techniques are directed toward reducing the hot carrier degradation and the SILC problems of specific semiconductor devices. They are not directed toward increasing the resistance of the overall circuit to damage caused by external radiation. Accordingly, there is a need for an annealing technique that can accomplish this and in particular that can improve the radiation hardness of the field or isolation oxides used throughout semiconductor circuits.

## Summary of Invention

[0008] According to one aspect of the present invention, a silicon-based semiconductor microcircuit is radiation hardened by replacing the standard finished circuit anneal process by heating the microcircuit in a vacuum furnace to remove any hydrogen in the microcircuit structure and annealing the microcircuit with deuterium containing forming gas. This process significantly increases the radiation hardness of the circuit while at the same time reducing hot carrier degradation and electrical stress induced leakage currents of individual circuit components.

[0009] Other aspects and advantages of the present invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawing, illustrating by way of example the principles of the invention.

## Brief Description of Drawings

[0010] FIG. 1 is a plot of the ratio of the flat band voltage shifts in hydrogen and deuterium annealed capacitor structures as a function of X-ray dose for various electrical fields applied during the irradiation process.

## Detailed Description

[0011] Typical silicon-based semiconductor circuits are made up of various devices, e.g., transistors, interconnect lines between the various devices, and isolating dielectrics separating the devices and interconnects from each other. Of these components, the isolating dielectrics are the most susceptible to damage from external radiation. The annealing process of the present invention significantly improves the radiation hardness of these circuits while at the same time reducing hot carrier degradation and electrical stress-induced leakage currents in the individual devices of which the circuit is partly comprised.

[0012] One aspect of the invention is the unique post-fabrication annealing process applied to the semiconductor circuit. First, the finished circuit is baked in a vacuum ( $<10^{-6}$  torr) for approximate one hour at about 500 ° C to remove any hydrogen in the circuit resulting from the fabrication process. The temperature of this out-gassing anneal stage is chosen to enhance removal of any hydrogen preexisting in the circuit from earlier process steps. Generally the temperature will be in the range of 400 to 700 ° C. The furnace temperature is then reduced and the circuit allowed to stabilize. After stabilization, the furnace is backfilled with deuterium-containing forming gas and annealed. This passivating anneal is carried out in a forming gas atmosphere in which the usual hydrogen component is replaced by deuterium. The temperature and duration of the passivating anneal is comparable to that customarily used in the passivating anneal process, e.g., 30 minutes at 420 ° C. This annealing process significantly improves the radiation hardness of the circuit.

[0013] A microcircuit can also be radiation hardened to an extent by skipping the out-gassing step and using deuterium-containing forming gas rather than hydrogen in the otherwise standard final passivating anneal. As a further refinement, radiation hardening of a microcircuit is improved by substituting deuterium at each step in the microcircuit fabrication process whenever hydrogen gas or hydrogen containing species are otherwise used.

[0014] An experiment to determine the effectiveness of the radiation hardening process was performed that measured the amount of radiation-induced charge in

the isolating oxide of a semiconductor circuit. Standard 20-nm thick  $\text{SiO}_2$  films were grown on p-type silicon wafers in a dry oxygen atmosphere. A 200-nm thick polycrystalline silicon film was deposited on the oxide. It was implanted with P ions ( $3 \times 10^{15} \text{ cm}^{-2}$  at an energy of 40 keV) and subsequently annealed for 3 minutes at 1000 °C in order to redistribute the dopant species in the polycrystalline layer and electrically activate them. MOS capacitor pads were etched in the 200 nm film (areas 0.00093 0.0028  $\text{cm}^{-2}$ ) using a lithographic process and dry etching ( $\text{XeF}_2$  gas). The finished capacitor structures were then annealed for about 1 hour at 520 °C in vacuum ( $< 10^{-6}$  torr) to remove any hydrogen in the structure (introduced, for example during the polysilicon deposition process). The furnace temperature was then reduced to 420 °C. After stabilization the furnace tube was backfilled with either deuterium-containing forming gas or hydrogen-containing forming gas. The anneal time was 30 minutes.

[0015] Capacitance/voltage measurements were obtained using the capacitor structures post-irradiation from an ARACOR X-ray source (tungsten electrode). The irradiations were carried out either with the top electrode and silicon substrate shorted electrically or with an electric field of  $\pm 0.5 \text{ MV cm}^{-1}$  applied across the oxide. Post-irradiation the capacitance/voltage characteristics were again measured and the evolution of the flat band voltage and the density of interface states measured. A series of measurements of the flat band voltage shift were obtained as a function of electric field applied during irradiation and of the irradiation dose.

[0016] The flat band voltage shift ( $\Delta V_{\text{FB}}$ ) is directly related to the amount of radiation induced charge in the oxide. The flat band voltage shifts were characterized from the un-irradiated capacitor values as  $\Delta V_{\text{FB}}(\text{D}_2)$  and  $\Delta V_{\text{FB}}(\text{H}_2)$  for the cases of deuterium annealed oxide and hydrogen annealed oxide. The ratio  $\Delta V_{\text{FB}}(\text{H}_2) / \Delta V_{\text{FB}}(\text{D}_2)$  was calculated and plotted it in FIG. 1. Since the ratio of flat band voltage shifts is greater than unity one can conclude that the radiation sensitivity is significantly reduced in the oxides annealed in deuterium containing gas as compared to those annealed in the hydrogen containing gas. The hydrogen-annealed capacitors were found to be approximately 50% more sensitive,

1970-1971	1971-1972	1972-1973	1973-1974	1974-1975	1975-1976	1976-1977	1977-1978	1978-1979	1979-1980	1980-1981	1981-1982	1982-1983	1983-1984	1984-1985	1985-1986	1986-1987	1987-1988	1988-1989	1989-1990	1990-1991	1991-1992	1992-1993	1993-1994	1994-1995	1995-1996	1996-1997	1997-1998	1998-1999	1999-2000	2000-2001	2001-2002	2002-2003	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022	2022-2023	2023-2024	2024-2025	2025-2026	2026-2027	2027-2028	2028-2029	2029-2030	2030-2031	2031-2032	2032-2033	2033-2034	2034-2035	2035-2036	2036-2037	2037-2038	2038-2039	2039-2040	2040-2041	2041-2042	2042-2043	2043-2044	2044-2045	2045-2046	2046-2047	2047-2048	2048-2049	2049-2050	2050-2051	2051-2052	2052-2053	2053-2054	2054-2055	2055-2056	2056-2057	2057-2058	2058-2059	2059-2060	2060-2061	2061-2062	2062-2063	2063-2064	2064-2065	2065-2066	2066-2067	2067-2068	2068-2069	2069-2070	2070-2071	2071-2072	2072-2073	2073-2074	2074-2075	2075-2076	2076-2077	2077-2078	2078-2079	2079-2080	2080-2081	2081-2082	2082-2083	2083-2084	2084-2085	2085-2086	2086-2087	2087-2088	2088-2089	2089-2090	2090-2091	2091-2092	2092-2093	2093-2094	2094-2095	2095-2096	2096-2097	2097-2098	2098-2099	2099-2100	2100-2101	2101-2102	2102-2103	2103-2104	2104-2105	2105-2106	2106-2107	2107-2108	2108-2109	2109-2110	2110-2111	2111-2112	2112-2113	2113-2114	2114-2115	2115-2116	2116-2117	2117-2118	2118-2119	2119-2120	2120-2121	2121-2122	2122-2123	2123-2124	2124-2125	2125-2126	2126-2127	2127-2128	2128-2129	2129-2130	2130-2131	2131-2132	2132-2133	2133-2134	2134-2135	2135-2136	2136-2137	2137-2138	2138-2139	2139-2140	2140-2141	2141-2142	2142-2143	2143-2144	2144-2145	2145-2146	2146-2147	2147-2148	2148-2149	2149-2150	2150-2151	2151-2152	2152-2153	2153-2154	2154-2155	2155-2156	2156-2157	2157-2158	2158-2159	2159-2160	2160-2161	2161-2162	2162-2163	2163-2164	2164-2165	2165-2166	2166-2167	2167-2168	2168-2169	2169-2170	2170-2171	2171-2172	2172-2173	2173-2174	2174-2175	2175-2176	2176-2177	2177-2178	2178-2179	2179-2180	2180-2181	2181-2182	2182-2183	2183-2184	2184-2185	2185-2186	2186-2187	2187-2188	2188-2189	2189-2190	2190-2191	2191-2192	2192-2193	2193-2194	2194-2195	2195-2196	2196-2197	2197-2198	2198-2199	2199-2200	2200-2201	2201-2202	2202-2203	2203-2204	2204-2205	2205-2206	2206-2207	2207-2208	2208-2209	2209-2210	2210-2211	2211-2212	2212-2213	2213-2214	2214-2215	2215-2216	2216-2217	2217-2218	2218-2219	2219-2220	2220-2221	2221-2222	2222-2223	2223-2224	2224-2225	2225-2226	2226-2227	2227-2228	2228-2229	2229-2230	2230-2231	2231-2232	2232-2233	2233-2234	2234-2235	2235-2236	2236-2237	2237-2238	2238-2239	2239-2240	2240-2241	2241-2242	22
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